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Isotope Effect in Superconductivity

Recent low-temperature experiments conducted by Dr. Emanuel Maxwell of the National Bureau of Standards have resulted in the discovery of a new and wholly unexpected relationship between superconductivity—the loss of electrical resistance at very low temperatures—and the constitution of the atomic nucleus. It was found that the pure mercury isotope 198 becomes superconducting at a temperature about 0.02 degree K higher than does natural mercury, which is a mixture of five different isotopes having an average atomic weight of 200.6.¹ As the difference between the isotopes depends entirely on their nuclear masses, this shift, which is proportionately quite large for a temperature so near absolute zero, indicates that the nucleus must exert an important effect on the superconducting properties of the metal.

Until now it has been generally supposed that superconductivity is concerned exclusively with the properties of the electronic configuration outside of the nucleus. However, the results obtained at the Bureau, in combination with an independent and almost simultaneous discovery of the same phenomenon in other mercury isotopes at Rutgers University,² establish the validity of the nuclear effect beyond question. The two researches are complementary and when taken together provide a conclusive demonstration of the effect.

The phenomenon of superconductivity, characterized by the complete disappearance of the electrical

resistance of metals such as lead and tin at liquid-helium temperatures, was discovered in 1911 by the Dutch physicist, H. Kamerlingh Onnes. Soon after this discovery, it was found that resistance reappears when a large electric current is sent through a superconductor or when a sufficiently strong magnetic field is applied. In 1918, Dr. F. B. Silsbee of the National Bureau of Standards postulated³ that resistance is restored when the magnetic field reaches a value known as the *critical field*, regardless of whether the field is applied externally or is caused by the current in the conductor. This theory, known as the Silsbee hypothesis, has been verified for pure metals in numerous experiments.

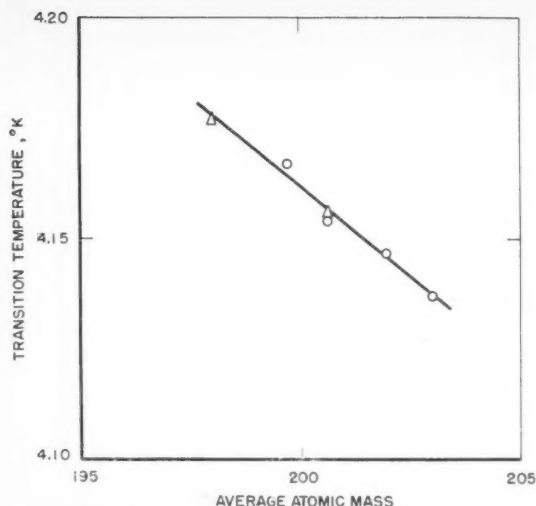
Although a great deal of research has been done in the last few years on the remarkable properties of matter at low temperatures, there is as yet no adequate theoretical explanation of superconductivity. To provide a basis for a better understanding of the properties of matter, the National Bureau of Standards is now making studies seeking a more complete explanation of this and other low-temperature phenomena. In the course of these studies, it was suggested that the *transition temperatures* at which different isotopes of the same element become superconducting be investigated to determine whether the mass of the atomic nucleus has any effect on this temperature.⁴

³ Note on electrical conduction in metals at low temperatures, Francis B. Silsbee, Bul. BS 14, 301 (1918) 8307.

⁴ Earlier experiments by Kamerlingh Onnes (1925) and Justi (1941) on the transition temperature of uranium lead (a lead derived from uranium by natural radioactive decay processes; atomic weight, 206.0) as compared with that of natural lead (atomic weight, 207.2) had indicated no deviations within experimental error.

¹ E. Maxwell, Phys. Rev. 78, 477 (1950).

² C. A. Reynolds, B. Serin, W. H. Wright, L. B. Nesbitt, Phys. Rev. 78, 487 (1950).



A smooth curve is obtained when the transition temperatures at which the various isotopes of mercury become superconducting are plotted against their average atomic masses. NBS data, Δ ; Rutgers University data, \circ .

Actually, the transition temperatures of the mercury samples were not measured directly. Instead, the critical field was measured as a function of temperature in the neighborhood of the normal, or zero-field, transition temperature. Then, by extrapolating to zero field, the normal transition temperature was accurately determined.

In measuring the critical field, use was made of the Meissner effect, or zero induction property. This is the name given to the property of a superconductor that prevents a magnetic field from existing within it. Thus, if a superconductor is brought into a magnetic field, the field cannot penetrate to the interior. Alternatively, if the metal becomes superconducting while immersed in a magnetic field, the field is immediately expelled. In other words, a superconductor acts like a perfectly diamagnetic material.

In the Bureau's experiment, the superconductor, a long thin needle of mercury enclosed within a sealed capillary tube, was placed inside a pick-up coil consisting of many turns of fine wire. The superconductor and pick-up coil were immersed in liquid helium within a Dewar flask surrounded by liquid air, and the pick-up coil was connected to a ballistic galvanometer. The critical field for a given temperature was then obtained by slowly increasing the current in a set of Helmholtz coils surrounding the liquid air bath. When the critical field was reached, the specimen suddenly lost its superconductivity and was penetrated by the magnetic field of the Helmholtz coils. The resulting change in flux linkages in the pick-up coil induced a voltage that caused a deflection of the galvanometer.

By varying the pressure within the Dewar of liquid helium, the temperature of the specimen was controlled in the range between 1.5° and 4.2° K with relative



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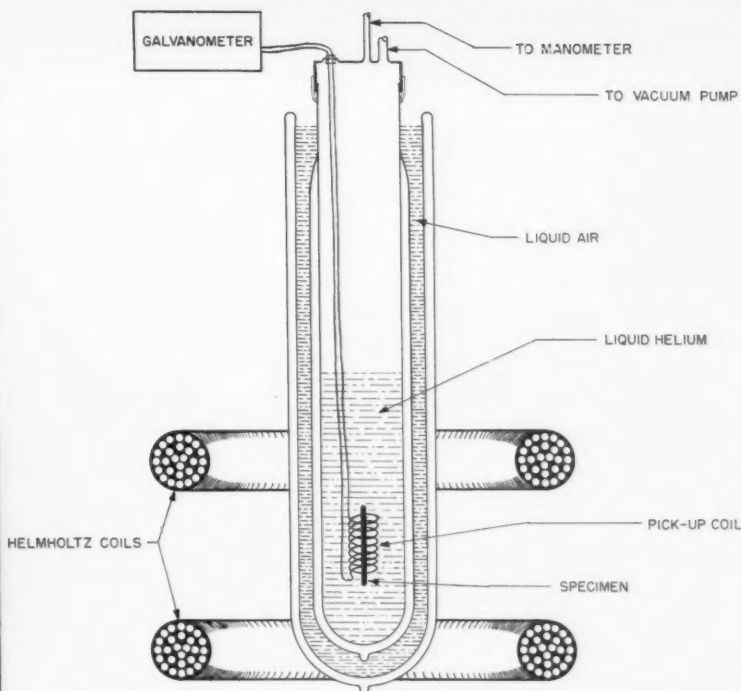
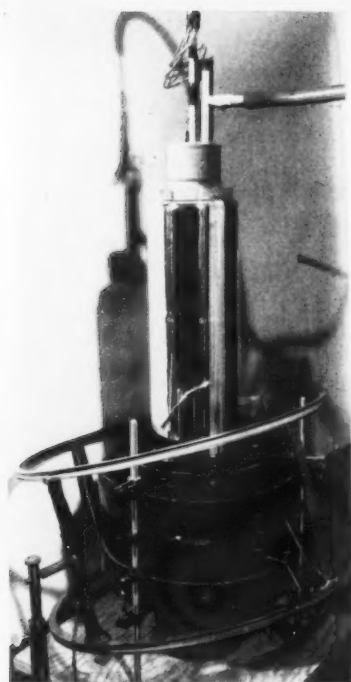
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ease. The experiment was repeated at a number of different temperatures, and the critical field was determined for each temperature. The critical field was then plotted against temperature, and the resulting curve was used to determine the transition temperature of the material under study. In this way it was found that pure Hg^{198} has a zero-field transition temperature of 4.177° K as compared with 4.156° K for natural mercury.

To make sure that the effect observed was due to the difference in mass and not to chemical impurities present, the mercury samples were carefully distilled to rid them of impurities. As the mercury had originally been prepared by bombarding gold with neutrons, there was some possibility of residual gold contamination. However, it was not possible to make a spectrochemical analysis of the Hg^{198} ; instead 0.1 percent of gold was added to some natural mercury, and the critical field curve of this material was determined. Within experimental error there was no difference between the curve for pure natural mercury and that for mercury with gold added. It was therefore concluded that gold contamination, if present in the Hg^{198} , was unimportant.



This apparatus is used at the NBS to investigate the isotope effect in superconductivity. The large silvered vacuum flask (left) contains a second vacuum flask surrounded by liquid air. Within the second flask is a superconducting specimen immersed in liquid helium and surrounded by a pick-up coil. The critical field for a given temperature is obtained by slowly increasing the current in the black Helmholtz coils encircling the outer flask until the specimen loses its superconductivity. When this occurs, a voltage is induced in the pick-up coil, causing a deflection in the galvanometer. The large tilted coils serve to counteract the effect of the earth's field.

As yet the true significance of the relationship between nuclear mass and superconducting transition temperature is not clearly understood. It has been suggested that the shift in transition temperature with nuclear mass may be associated with a corresponding change in atomic spacing. As it has already been found that an increase in spacing due to stress results in a higher transition temperature, this suggestion offers interesting possibilities that are now being explored at the Bureau.

In the work at Rutgers University, samples of mercury that had been enriched electromagnetically in each of the three isotopes Hg^{199} , Hg^{202} , and Hg^{204} , respectively, were studied. Although these samples did not have the high degree of isotopic separation of those used at the Bureau, they provided a greater number of

individual isotopes for comparison with natural mercury. When the Bureau's results are combined with those of Rutgers in a plot of transition temperature against average atomic mass, a smooth curve is obtained that shows a definite relation between the temperature at which mercury becomes superconducting and the mass of its atoms.

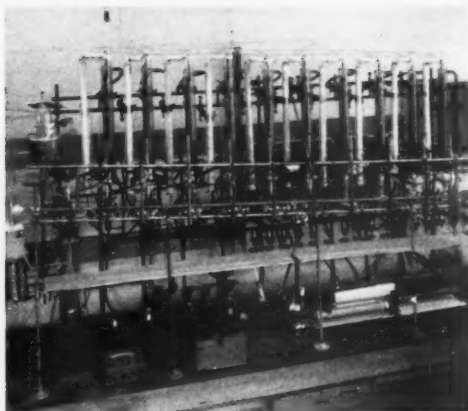
Since the initial discovery of the isotope effect in the superconductivity of mercury, a sample of tin consisting mainly of Sn^{124} has been investigated at the Bureau and found to exhibit a similar shift in transition temperature. The sample contained other tin isotopes as impurities, so that its average atomic mass was 123.1. The transition temperature determined at the Bureau was 3.662°K , as compared with a value of 3.715° for natural tin, whose atomic mass is 118.7.

Multicolumn Reflux Still

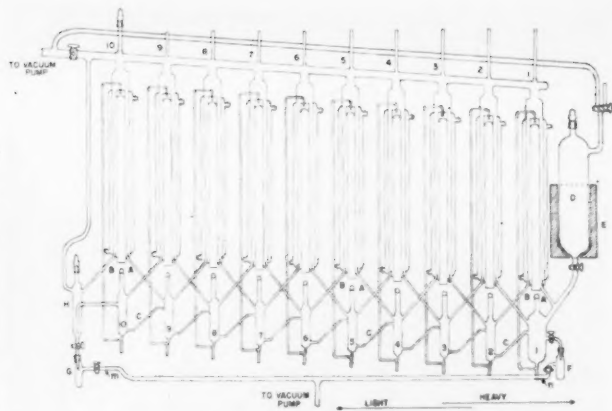
A multicolumn countercurrent molecular still designed by Dr. S. L. Madorsky of the National Bureau of Standards appears to have significant advantages for the commercial separation of liquids that differ in their molecular weights or vapor pressures but have similar properties otherwise. The columns of the still⁵ are

arranged in such a way that the condensates move by gravity from column to column in one direction, while all the residues move similarly in the opposite direction. Countercurrent refluxing with automatic recombination of fractions is thus obtained, and the desired separation of fractions is accomplished in a single operation. Among important possible applications of the new device are the concentration of vitamins from

⁵ For further details, see A multicolumn countercurrent still, by Samuel L. Madorsky, J. Research NBS **44**, 135 (1950) RP2061.



The NBS 10-column countercurrent molecular still provides means for separating liquids that do not differ appreciably in boiling point or that cannot withstand temperatures of ordinary distillation. The columns are arranged (diagram, right) so that residues flow to the right (outlet *A*) and condensates to the left (*B*). Magnetic pumps in the reservoirs move the liquid to the tops of the columns. Overflow tubes *C*, connecting the reservoirs, prevent excessive concentration of liquid in any one reservoir.



natural sources and the purification and concentration of vegetable oils, animal fats, lubricating oils, and high-boiling petroleum fractions.

The term molecular distillation has been applied to that type of distillation where there is no return of escaping molecules to the evaporating surface. This is accomplished by operating with high-boiling (low-vapor-pressure) liquids under such high vacuum that the mean free path of the escaping molecules is of the order of the distance between the surface of the evaporating liquid and the cooled condensing surface of the still.

In molecular distillation, the relative rates of escape of various kinds of molecules from a composite liquid surface are determined by two factors: (1) the vapor pressure (or the boiling point) of each component, and (2) the average molecular velocity of each component. Since molecular velocities, at a given temperature, are inversely proportional to the square roots of the atomic weights, molecular distillation offers a very practical means for the separation of any mixture of high-boiling substances differing in molecular or atomic weight. It is especially useful in the separation of hydrocarbons that do not differ appreciably in boiling point or are unable to withstand the high temperatures of ordinary distillation.

To avoid the necessity of making repeated cuts, with consequent reduction in output, countercurrent molecular stills have been designed in which a number of single-stage stills are so connected that recombination of fractions takes place automatically by gravity feed.⁶ Then the material to be concentrated can be fed into the system at one end, or at the midpoint if both light and heavy fractions are of interest; and the concentrate can be withdrawn continuously. Countercurrent stills of this type consist of a long column placed at a small angle to the horizontal and divided into cells with an

evaporating surface of a few square centimeters for each cell. Such stills have one disadvantage. As the openings between the cells must be relatively large, some mixing of vapor takes place; thus each cell represents merely a subdivision of the column and not an actual single-stage column.

In the multicolumn still developed at the Bureau, each column corresponds to a single cell in the earlier types of countercurrent stills. Mixing of the vapor between stages is thus eliminated, with a corresponding increase in the efficiency of the distillation process. To permit operation on a commercial scale, a large evaporating surface is provided, and the evaporating liquid is spread in a thin film to reduce the hold-up. In addition, the thin film is kept in continuous motion over a rough granular surface; this causes thorough mixing and thus prevents depletion of the lighter constituents.

The Bureau's still consists of 10 columns of Pyrex glass, although any number of columns can be used, and they may be made of other materials such as metal. The columns are arranged in a line at successively higher levels and are connected in such a way that the residues or heavy fractions flow from column to column in the downward direction, while the condensates or light fractions are pumped from column to column in the upward direction. The over-all operation is such that the light fraction increases in concentration near the lower end.

Each column consists of a central tube, which serves as an evaporator, surrounded by a water-cooled condenser. Below every column is a combination of magnetic pump and reservoir. The liquid is pumped from the reservoir through a feed line into a distributing cup at the top of the column, and from there it spreads over the evaporator in a thin layer. A short ring partition at the lower end of the annular space between the evaporator and condenser forms two concentric annular troughs with a separate outlet from each trough. These troughs and outlets separate the residue flowing down

⁶ Countercurrent reflux still for isotope separation, NBS Technical News Bulletin, 31, 33 (1947).

the evaporator from the condensate flowing down the condenser. The residue from each column, except the lowest, flows into the reservoir of the adjacent lower column; and condensate from each column, except the highest, flows into the reservoir of the adjacent higher column. The residue from the lowest column flows back into its own reservoir, while condensate from the highest column flows into a light fraction receiver and from there into the reservoir of the highest column. A large reservoir surrounded by a nichrome heater serves to degas the liquid before it is introduced into the still. Then, in passing through each feed line, the material is preheated to a temperature near that of the evaporator.

The evaporator is 45 centimeters long and has an outside diameter of 2.5 centimeters. This provides an evaporating surface of over 300 square centimeters. To facilitate uniform distribution and mixing of the liquid layer, the evaporating surface is covered with a thin layer of sintered powdered glass. As the condenser tube has an inside diameter of 4.1 centimeters, the distance between the evaporating and condensing surfaces across the annular space is 0.8 centimeter.

The magnetic pump at the base of each column consists essentially of a piston fitting closely within the glass reservoir tube and containing an iron core at its upper end. A solenoidal coil surrounds the glass tube in the region of the iron core. When a current flows in

the solenoid, the piston moves up and draws liquid from the reservoir through a check valve into a space below the piston. Then when the current is off, the piston drops by gravity, closing the check valve and forcing the liquid through another check valve into the delivery tube.

In a multicolumn still of this type, unless precautions are taken, a gradual accumulation of liquid in some reservoirs and a depletion in others may be expected. This difficulty is avoided in the Bureau's apparatus in two ways: First, the magnetic pumps are constructed as uniformly as possible, and the amplitudes of the pump pistons are equalized. Second, the evaporating rate is adjusted to a little over one-half the rate at which liquid is pumped into the distributing crown of each column, and the excess condensate is allowed to flow by gravity through overflow tubes from column to column in the downward direction. This arrangement also serves to reflux the light fractions from the light reservoir down to the lowest reservoir.

The new multicolumn still should permit large savings of time, labor, and materials, since it makes the process of fractionation in molecular distillation a continuous operation. An additional advantage lies in the fact that the entire separation can be carried out without exposing the condensate or residue to the atmosphere; this is particularly desirable for liquids that are susceptible to decomposition upon exposure to air.

Polarized Light Shows Nature of Plastic Deformation in Monel Metal

The ability of a metal to deform plastically without breaking enables it to withstand the inevitable misalignments and changing stress conditions that occur in machines and structures. Likewise, the shaping of a metal by rolling, pressing, drawing, or forging is dependent on its ability to deform plastically. A thorough knowledge of the factors involved in the plastic deformation of metals thus becomes highly important in obtaining maximum service from machine parts and other metal products.

Changes in the orientation of the crystals, or grains, that make up the commercial metals are known to play an important part in the deformation process. However, attempts to study grain orientation by the usual X-ray diffraction methods have been rather unsuccessful where only minute areas are involved. An obvious difficulty, for example, has been the identification of the area from which the diffraction pattern was obtained. Recently, D. H. Woodard of the National Bureau of Standards, in the course of a study of plastically deformed Monel metal, developed a technique¹ that uses polarized light to make visible differences in orientation that result from the deformation of a fully annealed specimen. Though use of the technique has thus far been confined to Monel, the method is expected

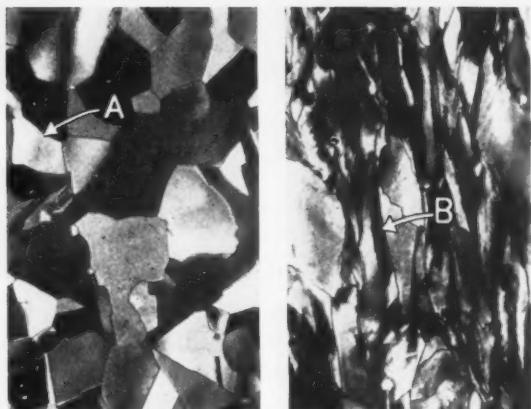
to find application in studies of plastic deformation in other metals.

When Monel is polished and treated with most etchants, it is optically isotropic, reflecting polarized light equally in all directions. However, when specimens were given a light etch (about 4 seconds) with the Monel Contrast Etch (an aqueous solution of chromic and nitric acids and ammonium chloride), the surface of the metal became optically active. Under these conditions polarized light can be used to detect differences in grain orientation.

Monel that had been annealed so as to give uniform point-to-point orientation within individual grains was viewed microscopically under polarized light with polarizing elements in the incident and reflected beams crossed. The intensity of the reflected light was uniform over each grain. However, when the annealed Monel was deformed before being sectioned and polished, the intensity of the reflected light was no longer uniform over the individual grains. It was thus possible to study visually those regions that had undergone changes in orientation.

Tensile specimens that had been given different amounts of plastic extension were sectioned and polished and used to study the effect of increasing plastic deformation on the changes in orientation within individual crystals. From the irregularity of these changes, it was evident that directions of flow varied within small

¹ For more complete details, see Stages in the deformation of Monel metal as shown by polarized light, by D. H. Woodard, *Metals Trans.* **185**, 722 (1949).



Increasing plastic deformation in Monel metal is shown by the Bureau's new technique. Broad diffuse bands (grain A) appear with slight plastic deformation. After severe necking of the specimen, fully formed deformation bands are outlined (grain B).

areas and that the deformation in individual grains was by no means uniform or regular. Furthermore, the deformation was confined neither to the areas near the grain boundaries nor to the center of the grains but depended upon the orientation of adjacent crystals and the direction of the stresses they imposed.

Thin, straight parallel lines known as "slip lines" are usually visible on polished and etched surfaces of annealed metals after slight deformation. Sometimes these lines are curved on specimens that have been deformed previously. There has been some question as

to the interpretation of this curvature. Some investigators have suggested that a group of such curved lines represents a set of crystallographic planes that are bent; others contend that the curves are the traces of several sets of parallel crystallographic planes that remain straight but combine to give the effect of curved lines. Use of polarized light at the Bureau to show differences in orientation along the length of a line indicated that the slip lines were traces of crystallographic planes that had been bent prior to the formation of the slip lines. Some of the differences in orientation observed in individual grains, which were more pronounced after severe plastic deformation, may therefore be interpreted as bending of the crystal lattice. This bending of the crystals during plastic deformation leads to the development of deformation bands. As deformation proceeded, these bands behaved as individual crystals and thus could be considered as fragments of the original crystal.

It was found that the total intensity of the combined reflections from many grains varied as the specimen was rotated with respect to the plane of polarization. Since this integrated intensity increased with greater deformation, it appeared that polarized light might be used to detect preferred orientation resulting from such shaping processes as drawing, rolling, and stamping. Preliminary results indicate that the Bureau's method is more sensitive than X-ray diffraction methods for this purpose. Recently it has been found that other cubic metals, such as copper, aluminum, nickel, and alpha iron, can be made optically active. Thus this new application of polarized light can be used in the study of a number of commercial metals.

Improved Magnetic Permeameter

An improved magnetic permeameter for the precise testing of magnetic materials at magnetizing forces up to 300 oersteds has been developed by R. L. Sanford and P. H. Winter of the National Bureau of Standards. The new instrument, known as the MH (medium magnetizing force) Permeameter,⁵ is absolute in principle—that is, its constants are derived from its own dimensions so that calibration by reference to any other permeameter is not required. At the same time it is as simple and convenient to operate as any of the commercial permeameters now in general use in industrial laboratories.

Magnetic materials are essential to the satisfactory operation of practically all electrical equipment, with the exception of incandescent lamps and heating devices. Recently their use has been extended even further through the development of new and superior magnetic alloys for many special applications. Of basic importance in the production and utilization of these materials is the accurate determination of their magnetic properties. Such data are needed not only

by those who purchase on specification but also by manufacturers in order to maintain uniformity of product and to provide information for use in design. Normal induction and hysteresis data are commonly obtained in industrial laboratories by the use of several different types of commercial permeameters. To secure uniformity in this work, specially prepared test specimens of magnetic materials used by the various laboratories as reference standards in calibrating their permeameters are periodically submitted to the Bureau's magnetic measurements laboratory for test.

For many years the testing of magnetic reference standards has been carried out with the Burrows Compensated Double-Yoke Permeameter, an instrument developed at the Bureau in 1909. Although this permeameter gives highly accurate results when properly used, it is not nearly as convenient as the commercial permeameters now available. For example, it requires duplicate specimens, is complicated and time-consuming to operate, and is very sensitive to any lack of uniformity in magnetic properties along the length of the specimen. The Bureau therefore undertook the development of a permeameter that would be comparable in accuracy to the Burrows permeameter but

⁵ For further technical details, see A permeameter for magnetic testing at magnetizing forces up to 300 oersteds, by Raymond L. Sanford and Philip H. Winter, J. Research NBS 45, 17 (1959) RP2109.

would have the convenience in use of the more common commercial permeameters.

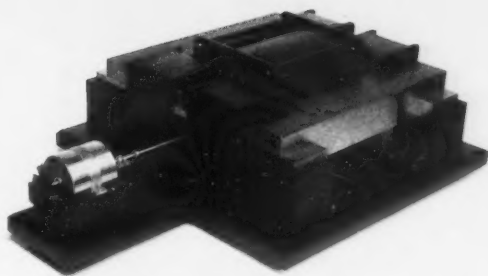
The permeameter designed at the Bureau consists essentially of a main magnetizing coil, which surrounds the specimen, and two symmetrical U-shaped core pieces or yokes, which complete the magnetic circuit and thus serve to promote a uniform cross-sectional distribution of magnetic flux in the specimen. The yokes are arranged to form a square bisected by the specimen, a bar of rectangular cross section, and are supported by two end pieces, rectangular bars of magnetic material at either end of the magnetizing coil. The end pieces, which rest on four Bakelite blocks, also support the specimen and provide for good magnetic contact between the yokes and the specimen. Auxiliary magnetizing coils, encircling the ends of the yokes and the supporting end pieces, tend to promote a uniform longitudinal distribution of flux in the specimen by overcoming the contact reluctance between the specimen and the yoke. The flux distribution in the region about the center section of the specimen is thus improved, and the accuracy of measurements of magnetizing force is correspondingly increased.

Values of flux-density, B , are obtained by measuring the electrical impulse in a test coil surrounding the bar at the middle. An auxiliary test coil whose area-turn value is adjusted to be equal to that of the B -coil is located adjacent to the B -coil but not surrounding the specimen. As the auxiliary coil is connected in series with the B -coil in such a way that the two currents are in opposition, the galvanometer deflections observed are a measure of the intrinsic flux density rather than the total flux density. This eliminates the necessity of calculating the air-flux correction for bars of different cross-sectional area.

Values of magnetizing force, H , are obtained by means of two H -coils so mounted that they can be made to rotate through 180° in the region adjacent to the center section of the specimen. The H -coils are set one above the other on a rotating brass table and adjusted to equal area-turn values. When these coils are connected in series, with their currents opposing and their axes parallel to the specimen, and are rotated through 180° , the galvanometer deflection observed is proportional to the radial gradient of the field measured outward from the surface of the specimen. The value of H as determined by the deflection when only the upper coil is connected to the galvanometer is then extrapolated to the surface of the specimen by use of the observed value of the radial gradient.

Rotable H -coils, or "flip-coils," have been found to have certain definite advantages over stationary H -coils. For example, identity in the observed values of magnetizing force for both directions of the magnetizing current is a good indication that the specimen is satisfactorily demagnetized. Also, by use of rotatable coils, values of magnetizing force for points on the hysteresis loop can be obtained by direct observation, with consequent improvement in precision and accuracy.

The over-all length of the yokes is 28 centimeters. While the specimen should preferably be of this



An improved magnetic permeameter has been developed for accurate testing of magnetic materials at magnetizing forces up to 300 oersteds. The specimen, a rectangular bar, is placed axially within the main magnetizing coil (center of apparatus). Two U-shaped core pieces on each side of the magnetizing coil complete the magnetic circuit and thus promote a uniform cross-sectional distribution of magnetic flux in the specimen.

length, bars as short as 24 centimeters can be tested if necessary. The main magnetizing coil is 13.8 centimeters long and consists of 1,540 turns of No. 18 AWG Formex-insulated magnet wire uniformly wound in 12 layers on a Bakelite form. The four compensating coils on the yokes are 5.8 centimeters long and consist of 430 turns of similar wire wound in eight layers.

It is estimated that the MH permeameter can be used to obtain values of induction accurate to within about 0.5 percent and values of magnetizing force accurate to within 0.5 percent or 0.05 oersted, whichever is larger. For routine tests, values of either quantity accurate to within 1 percent should easily be possible. As good contact between the yokes and specimen is obtained without the necessity of clamping, uncertainty in results due to the effect of mechanical strain on the specimen is avoided. This is a definite advantage in the testing of high-permeability alloy sheet, which is likely to be extremely sensitive to strain.

Control of Odors

A concise, readable presentation of the problem of undesirable household and industrial odors, together with practical methods for their control is given in a new circular, *Control of Odors*, just published by the National Bureau of Standards.

If an odor cannot be removed by either cleaning or by ventilation, it may be desirable to add something to the atmosphere of the room to make the odor less objectionable. The use of masking, anesthetic, and irritant effects for this purpose is explained. The principal sections discuss the control of industrial odors to prevent a nuisance in the neighborhood and the very different problem of control in households and places of business.

National Bureau of Standards Circular 491, *Control of Odors*, 12 large double-column pages, is available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., for 10 cents a copy.

Few office and public buildings of any consequence are constructed or remodeled today without some provision for acoustic treatment of their interiors. The fact that builders of large buildings allocate hundreds of thousands and even millions of dollars for acoustic treatment indicates the importance of acoustic materials in modern building technology. Unfortunately, the design and application of acoustic materials is often done arbitrarily. This is due in part to the complexity of the phenomenon of sound absorption by acoustic materials. All too often, however, manufacturers, architects, and applicators fail to use the information on acoustic materials that is already available.

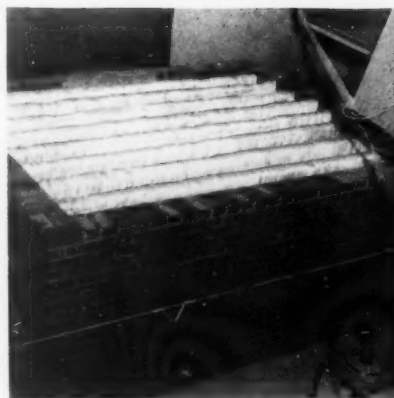
To remedy the situation, the National Bureau of Standards has been engaged since the beginning of the acoustic materials industry in an extensive program of research and development, involving all phases of architectural acoustics. This work has included the measurement of sound absorption and transmission for a wide variety of materials, the development of new types of sound-isolating structures, theoretical and experimental studies of sound-absorption and transmission processes, and the development of new instruments and techniques for acoustic measurements. Such knowledge, published primarily to guide Government agencies in the proper selection of commercially available materials, also aids business and industry as a whole to obtain more adequate control of noise levels, whether in architectural or product design. For a better understanding of the problems arising from the complicated sound absorption process, a brief review of the essential theory underlying acoustic materials, some of the principles governing their use, and methods of measurement should be helpful.

Acoustic materials present a two-sided problem. On one hand are the structural factors that influence their sound absorbing power. Then again, the behavior of sound itself in a house, office, church, or theater, continually intrudes to alter the apparent properties of acoustic materials. In some rooms, the sound absorbing power of a material can be quite different in different locations in the rooms. In this discussion only the factors pertaining to the materials themselves shall be emphasized.

Purpose of Acoustic Materials

Modern building materials and techniques lead to hard, smooth interior walls that are notoriously poor sound absorbers. After a source of sound, for instance a speaker's voice, is suddenly stopped in a room with hard plaster walls, the sound does not stop immediately. Rather, it is reflected from wall to wall, only a small fraction of its energy being absorbed at each reflection, until eventually the energy is so far reduced that the sound becomes inaudible. This persistence of sound after the source is stopped is called reverberation, and the time required for the energy of the original sound to decay to one millionth of its original value is called the reverberation time of the room.

Excessive reverberation is common and a serious defect in many churches, theatres, offices, and factory



Sound absorption coefficients of acoustic materials are measured in the National Bureau of Standards reverberation chamber. Diffusion of sound is accomplished by means of a brick enclosure during a measurement in the chamber. (Left) A highly sound absorbent structure, consisting of a 2-inch thick brick enclosure, is used for measuring the sound absorption coefficient of a sample. (Center) Acoustic plaster samples are arranged in a reverberation chamber. (Right) Felt-covered absorbent spheres were found to have good sound absorption properties.

rooms. Conversation in reverberant rooms is annoying. Preceding speech syllables overlap succeeding syllables and, if the reverberation time is very long, conversation becomes extremely difficult. Moreover, when noisy devices like typewriters or electric fans are operated in an excessively reverberant room, the general noise level builds up to a much higher level than it would be if the same appliances were operated in nonreverberant surroundings. Reverberation, however, is not without its benefits. The reinforcing effect of reverberant enclosures can actually serve to enhance speech and music, provided the reverberation time is held within certain limits. The acceptable limits for speech are from $1/2$ second for small rooms to about 1 second for large rooms. It is possible to predict in advance of construction, or remodeling, the amount of acoustic material that must be placed in a given room to obtain the optimal reverberation time. Acoustic materials have the ability to absorb much greater fractions of the energy of the sounds incident upon them than do ordinary plaster or masonry walls. In a room with walls treated with such materials, a sound wave undergoes many fewer reflections before it becomes inaudible.

The fraction of the incident sound energy that is absorbed at each reflection is called the sound absorption coefficient of the material. It is a dimensionless quantity with a range from zero to unity depending on the material and the frequency of the sound. For a smooth-finished solid masonry wall, it may be as low as 0.01 at very low frequencies. But sound absorption coverings with coefficients approaching the theoretical limit of 1.00 for most of the audible frequency range have been developed for lining special acoustic test rooms in which it is necessary to hold reverberation to a minimum.

Sound Absorption Processes

When a sound wave comes in contact with rigid porous material on the wall of a room, part of the incident sound energy is reflected back into the room by the surface of the material. The remainder is used to set in motion the air contained within the pores and voids of the material. In pores sufficiently narrow, viscous forces between the air and the walls of the pores oppose the motion of the air. Sound energy is transformed into heat as the wave progresses through the material and if the material is thick enough, all of the sound energy in that fraction of the wave that entered the material will be entirely dissipated. The usual acoustic materials, however, average somewhat less than an inch in thickness. In this short distance, even the more efficient absorbers usually cannot absorb all of the sound energy transferred to the air in the pores. The unabsorbed portion is propagated through the back surface only to be reflected back into the material by the wall on which the material is mounted. After suffering further reduction in energy, what is left of the sound wave emerges from the front surface to combine with the initially reflected portion.

The method of mounting an acoustic material can influence greatly its sound absorbing power. Numerous measurements⁹ reveal that an increase in the airspace back of a material increases its sound absorbing power, particularly at the lower frequencies.

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Architects and acoustic engineers often make use of this effect in prescribing acoustic treatment. At higher frequencies, other phenomena may enter the picture in such a way as to completely nullify the effects of spacing. Consequently, in the absence of adequate theory, the effects of mounting on the absorbing power of a particular acoustic material can be appraised only by direct measurement.

Types of Acoustic Materials

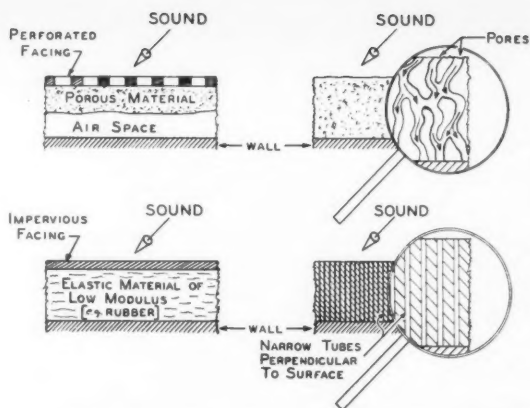
Acoustic materials are made from a great variety of substances and combinations of ingredients. Very efficient sound-absorbers have been made from vegetable fibers such as wood, bagasse, or cotton. Hair felt is still used but not to the same extent as formerly. Mineral fibers such as asbestos, glass, and mineral wool, enter into many compositions as well as do vermiculite, pumice, and perlite aggregates. The binding agent often can contribute considerably to the sound absorption of a product. The porosity of materials is often increased by the addition of a suitable foaming agent to the mix.

Acoustic materials made from these substances are available in several forms: (1) Prefabricated materials, (2) plasters, (3) sprayed-on materials, and (4) acoustic baffles. The architect resolves his choice of material by such considerations as cost per unit of absorption, appearance, cost of maintenance, fire resistance, and method of application. Resistance of acoustic materials to vermin infestation is of paramount importance in rooms where food is handled. Resistance to moisture is a requirement in damp locations, such as over swimming pools.

The architect may be interested in sound absorption coefficients at individual frequencies or in the average coefficient over a range of frequencies. By custom, acoustic treatment for auditoriums and theaters is specified in terms of the sound absorption coefficient at 512 cycles per second. When the problem is one of reducing noise levels in a room, the architect uses the "noise reduction coefficient," which is the average, to the nearest multiple of 0.05, of the sound absorption coefficients at 256, 512, 1,024, and 2,048 cycles per second. However, there is a trend toward specifications of acoustic materials for control of reverberation in auditoriums in terms of other frequencies in addition to 512 cycles per second.

Prefabricated Materials

Prefabricated acoustic materials are sold in the form of flat tiles or boards that are applied to the walls of a room. They may be cemented directly to the wall or ceiling by means of "acoustic cements" made especially for the purpose, or they may be nailed to furring, or supported on suspension systems. Frequently the edges of tiles are kerfed for the reception of splines, which assist in the alinement of the tiles to a true flat surface.



Schematic illustration showing the construction of common types of acoustic materials. Similar types of construction can be duplicated more or less in prefabricated units, as well as in materials for plastic application.

Since the manufacturing process for prefabricated materials can be accurately controlled, the chief advantage in using these materials is the assurance that the material will have the sound absorption coefficients specified by the architect. This cannot be said in general for the materials intended for plastic application. The manipulation of the material on the job site often cannot be closely controlled. Slight departures from formula, or even unusual drying conditions, may materially affect the plastic material's sound absorption.

Prefabricated materials are classified into different types on the basis of surface appearances. There is no choice between the different types as far as sound absorption is concerned, since there is a wide choice of coefficients available in each type (see footnote 9). But there is a greater difference in the ability of the different types to withstand redecoration by means of paint. The perforated and the deeply fissured materials may take a number of coats of paint, either brush or spray, without marked detriment to their sound absorbing power. This is not the case with many materials whose surface is close-textured. As will be shown later, the painting of these must be done with extreme care if the acoustic life of the material is to be preserved.

A large portion of acoustic tile sold in this country is applied directly to walls and ceilings by means of "acoustic cements", which are designed to adhere well to wood, gypsum wall board, and concrete. Obviously, walls covered with loose paint, or paint that may become loose in time, are not prime surfaces for this method of application. Also, acoustic cements should not be used if the wall is subject to "sweating" due to condensation of moisture. Newly constructed concrete and plaster walls often contain alkaline ingredients that have a deleterious effect on acoustic cements. Consequently, application of acoustic materials by means of acoustic cement should not be specified unless there is complete assurance that the wall surfaces are in prime condition.



Acoustic impedance is measured by a method that employs a bridge similar to the electrical bridge. One branch, however, is an acoustic link. This link is an adjustable tube; a sound source is mounted in one end and the sample in the other. A probe microphone is then used to explore the sound field around the sample.

Acoustic Plasters

Often the architect requires the acoustic treatment to be applied in broad areas, unbroken by visible tile or board joints. Acoustic plasters lend themselves admirably to this purpose. Unfortunately, acoustic plasters must be applied by skilled mechanics in order to obtain the rated sound absorption coefficients. The mix proportions and the recommended mixing time must be adhered to rigidly. Practically all commercially available acoustic plasters are properly compounded at the mill, and only water is added on the job. A slight change in the proportion of the water added to a batch of plaster¹⁰ may not only change its surface texture, but also may ruin its sound absorption.

Most acoustic plasters are applied over scratch and brown sanded-gypsum plaster base coats either on metal or gypsum lath. There are a number of acoustic plasters, however, that are applied on base coats of the same compositions as the acoustic plaster itself. On account of their lightness, these homogeneous plasters exhibit relatively large diaphragmatic absorptions at low frequencies.

Practically all acoustic plasters contain ingredients that are more or less soluble in water. During the drying process, the dissolved substances are carried to the surface where they are deposited. In some cases, the solubility of an ingredient is high enough so that a thin impervious film of solids completely closes the surface pores after the plaster has dried. Except at very low frequencies, where diaphragmatic absorption occurs, such plasters exhibit low absorbing power because the air cannot penetrate through the glazed-over surface into the inner pores and voids. Acoustic plas-

ters with a propensity toward glazing require stippling when partially dry to improve their sound-absorbing power.

In general, acoustic plasters may be steel troweled or cork, shingle, or mohair floated to produce various surface textures. The troweling or floating must be done at the proper time after application. The time interval specified by the manufacturer has been determined on the basis of numerous elaborate sound absorption tests on his plaster and should be adhered to closely. Premature troweling, or over-troweling, may bring the finely pulverized plasticizing ingredients, the so-called "fat", to the surface. An accumulation of fat tends to close off the surface pores with an effect on sound absorption similar to that of glazing discussed above. Troweling or floating too late may leave trowel marks and an uneven surface texture.

Sprayed-on Materials

A number of fibrous materials, notably asbestos and mineral wool, are applied on the job by spraying the shredded fiber, together with a suitable binder, directly on the surfaces to be acoustically treated. After spraying, the material is rolled or tamped to a smooth surface. Sprayed-on materials can have comparatively high sound absorbing powers (see footnote 9), depending on their porosity and thickness.

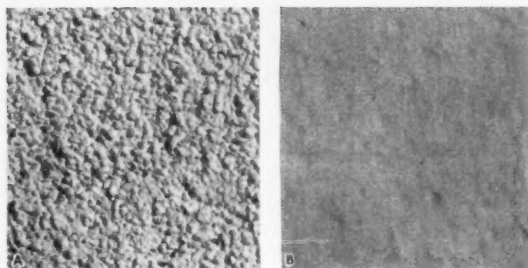
The chief disadvantage of sprayed-on materials is their structural weakness when applied too loosely or when insufficient binder is mixed with the shredded fiber during spraying. If insufficient binder is employed, shedding of the fiber may take place because of vibration of the wall surfaces to which the material is applied. Obviously, shedding of materials containing mineral wool can be very annoying to individuals confined to rooms where such shedding takes place. Excessive shedding may be prevented by addition of the requisite amount of binder during spraying, or by sizing or painting the finished surface. Inasmuch as sprayed-on materials are relatively soft, they are not adapted for use in locations like gymnasiums where they may be accidentally dented by a thrown ball or some other missile.

Yet it is this very structural weakness of sprayed-on materials that results in an acoustic material with very unusual characteristics from the standpoint of redecoration. Occasionally weak but exceptionally resilient materials are encountered that can be painted repeatedly until their surface pores are completely closed without marked diminution of their sound absorbing power. In fact, such materials may acquire additional absorbing power, especially at low frequencies, after repeated painting.

Acoustic Baffles

It often happens that in a room with large window areas, there is insufficient wall area for application of acoustic material to obtain the required reverberation time. In such instances, recourse is made to "acoustic

¹⁰ Although the ingredients differ widely, there is a general sort of scheme followed in compounding acoustic plasters. A porous ingredient like pumice, cork, or vermiculite is used to give body to the plaster. The cementitious material like gypsum, lime, or portland cement, not only serves as the binder, but also as the plasticizing medium necessary for application by trowel. A foaming agent is often incorporated to provide porosity. Fibrous materials like shredded asbestos, wood pulp, or cotton linters, increase cohesion during application and give added strength to the dry plaster. Some fibrous constituents shrink as they dry and so contribute to the porosity.



High porosity, such as found in a typical acoustic plaster (A), is a necessary characteristic for sound absorption; note the numerous small openings between the surface particles. When these openings are covered with a paint film (B), the absorption is largely lost.

baffles,"¹¹ i. e., sound absorbent structures that are placed away from the walls where they will not interfere with lighting from windows. Baffles are also used to isolate individual machines. When placed around a machine so as to partially enclose it, baffles absorb sound at the source before it has an opportunity to spread to regions in a room where it is desired to maintain a lower sound level.

To be effective, baffles must be very highly sound absorbent; this is achieved by the use of thick layers (3 to 6 inches) of porous materials. Fibrous materials like mineral wool or glass wool, encased within perforated metal or perforated asbestos board coverings, are often used for baffle purposes. Baffles may also be constructed of highly porous masonry especially developed for the purpose.

One of the more interesting applications of baffles has to do with the quieting of airplane engine test stands. During tests of airplane engines, provision must be made for practically unobstructed air intake and exhaust to and from the test rooms. The intake and exhaust stacks in modern test stands are about 20 feet long and about 20 by 20 feet square in cross section. The stacks are sometimes honeycombed with very porous masonry units. Frequently they are constructed of ribbon walls consisting of parallel sheets of perforated-metal-clad mineral or glass wool. The airborne sound produced by the engine is highly attenuated on passing through the honeycomb structure or between the ribbon walls of stacks.

Paintability

In common with all interior finish materials, acoustic materials must be painted periodically to restore a clean and attractive appearance. Unfortunately, painting is not always compatible with preservation of sound absorption. It is true that perforated and some fibrous materials offer no particular difficulties as to painting. Also, a number of sprayed-on materials may be painted repeatedly without much effect on their sound absorbing power. But for a large number of

porous nonperforated tiles and plasters, which require extreme care in painting, one injudicious coat of paint can practically ruin whatever acoustic properties the material had. The acoustic life of nonperforated materials may be prolonged indefinitely if the painting is done in accordance with procedures found by experiment at the National Bureau of Standards to be most advantageous.

First, nonperforated materials should always be spray painted—never brush painted. In trying to reach the sides of the deeper depressions or crevices in a rough surface, much more paint is applied by brush than by spray painting methods to obtain the same light reflectivity. When these crevices, which form the openings to the inner pores of a material, are filled, the surface becomes impervious to flow of air, and sound absorption is reduced. The reduction in efficiency is much more pronounced at the higher frequencies where flexural vibrations are not easily induced in material.

Even with spray painting, the paint should never be applied to bring the surface to the full color or shade of the paint. Rather, enough paint should be applied to hide the old surface only reasonably well. Beyond a certain point, addition of more paint does not enhance the color or increase the light reflectivity greatly, but it does lower the sound absorbing power disproportionately. The type of paint used apparently plays only a minor role.¹² Numerous experiments at the Bureau indicate that there is no preference between resin-emulsion or casein paints on the acoustic properties of a material. The factor that counts most is the amount of solids deposited in the pores. In general, the useful acoustic life of many unperforated, fine-textured materials can be considerably extended, when these materials are spray painted rather than brush painted.

Test Methods for Sound Absorption

Before an architect can specify the amount of a given material that is to be placed in a room to bring its reverberation time to a predetermined value, he must know the material's sound absorption coefficients. The difficulty is that the coefficients are not a unique property of the material. They depend on the manner of mounting, on the area, and to some degree on location of the material in a room. Only a method of measurement that takes all of these factors into account will yield absorption coefficients directly useful to the architect.

Reverberation Chamber Method

In this method, sound absorption coefficients are measured on large samples of the material, about 72 square feet in area, mounted exactly as they would be in an actual installation. Variations of absorption due to nonuniformity of the product are largely averaged-

¹¹ R. K. Cook and Peter Chranowski, Absorption and scattering by sound absorbent cylinders, *J. Acous. Soc. Am.* **17**, 315 (1946). Also in *J. Research NBS* **50**, 393 (1946) RP1709.

¹² V. L. Chrysler, Effect of paint on the sound absorption of acoustic materials, *J. Research NBS* **21**, 547 (1940) RP1298.

out. Moreover, the materials are measured in a sound field that approaches the type of sound field that exists in an actual large room. For these reasons, reverberation chamber coefficients are used universally for architectural purposes.

The reverberation chamber at the National Bureau of Standards is a large room of about 15,000 cubic feet. Its walls are made as reflecting as possible, so that reverberation times as long as 15 seconds can be obtained at the low and middle frequencies. Great precautions are taken to produce the uniform distribution of sound energy required by theory. The chamber is equipped with large rotating vanes to aid in diffusing the sound energy continually. The sound is produced by means of loudspeakers fed with frequency modulated ("warbled") test signals and is picked up by microphones. After amplification and filtering, the microphone output is led to a recorder that automatically plots the intensity of the decaying sound on a tape from which the reverberation times are determined. First the reverberation time of a chamber is measured when it is empty, and again when the sample is placed in the room. From the difference between the two reverberation times, and known constants of the room, the absorption of the sample is computed from a theoretical formula.

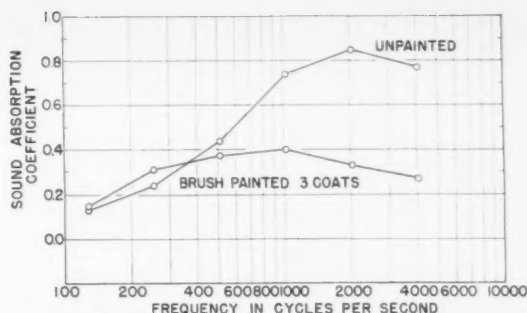
Area Effects

It is well known that the absorption of an acoustic material depends to a large degree on the size and shape of the sample tested. Because of diffraction effects, measurements on small samples indicate much greater absorptions per unit area of material than do measurements on larger samples of the same material. It is not unusual, even on a sample as large as 72 square feet, to obtain apparent absorption coefficients greater than unity.

From a large number of measurements on areas of various sizes and different materials, the Bureau has shown that the apparent absorption coefficient approaches a limiting value as the area of the test sample is increased indefinitely.¹³ Consequently, the sound absorption coefficients for surfacing materials obtained at the National Bureau of Standards are always reported after they have been corrected to what they would be for an infinite area. Obviously, such corrections cannot be applied to acoustic structure like irregularly shaped baffles. The results for baffles are reported in terms of the number of units of sound absorbing power actually measured for the particular number and arrangement of the baffles used in the sound absorption tests.

The area effect may be put to good use in acoustic treatment of rooms. A greater absorption than that indicated by the absorption coefficients can be obtained if the available material is distributed in small patches than if it is lumped into one area. The effect is most pronounced when the small patches are well separated.

¹³ V. L. Chrisher, Dependence of sound absorption upon the area and distribution of the absorbent material, J. Research NBS **43**, 169 (1934) RP700.



The effect of brush painting on the sound absorption of a typical acoustic plaster construction. After three coats this plaster has reached the limit of its useful life.

Tube Methods—Acoustic Impedance

A promising method for the determination of the absorption coefficients of a material depends on measurements of its acoustic impedance, a quantity that is analogous to electrical impedance. In one variation of this method a small sample of acoustic material closes one end of a tube, and a source of sound is placed at the other end in such a way that a system of standing plane waves of sound is set up in the tube. The standing wave is affected by the sound absorbent properties of the material. The acoustic impedance, and consequently the absorption coefficients, can then be determined from measurements of the source pressure variation in the standing wave.

The use of sound absorption coefficients determined by the tube method for architectural purposes is objectional because they are obtainable only for plane waves of sound incident perpendicularly on the material. In other words, the sound field in the tube is not random as it is in the reverberation chamber. No satisfactory technique has as yet been developed for measurement of acoustic impedance for angles of incident other than normal. However, recent attempts at correlation of tube coefficients with those measured in reverberation chambers have met with fair success. Unfortunately, mounting conditions encountered in actual installations cannot be duplicated on small scale tube samples nearly so well as they can be on the large scale sample used in the reverberation chamber. Consequently, although tube coefficients are not usually of direct use to the architect, they can be employed to advantage in development and manufacturing control of acoustic materials.

Box Method

Besides the reverberation chamber and the impedance tube methods, there is one other practical technique for measurement of sound absorption coefficients. In this so-called "box method"¹⁴ a sound field is created

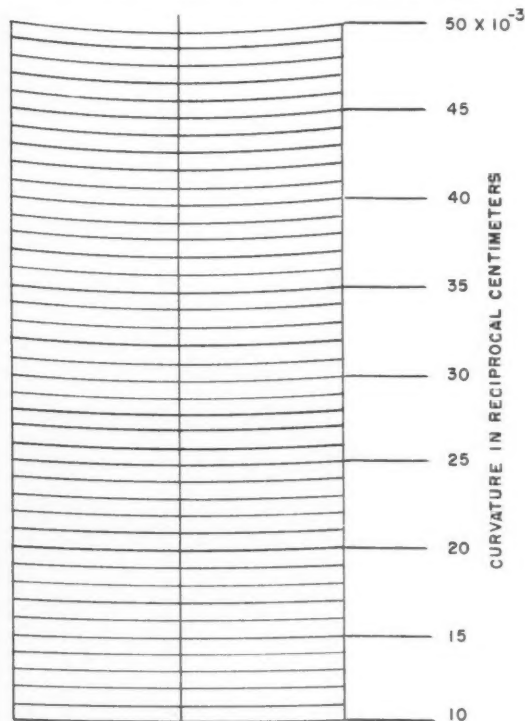
¹⁴ The box method described here was developed by V. L. Chrisher at the National Bureau of Standards and presents a greatly modified version of a similar method first employed by P. E. Sabine of Riverbank Laboratories (now part of Armour Research Foundation) at Geneva, Illinois.

in a box about a square foot in cross section with a variable length from about 2 to 3 feet. The sound is produced at one end of the box by a speaker and is picked up at the other end by a microphone. A sheet of metal bent into a right angle is placed in the box with the apex of the angle upward in such a way as to deflect the sound against the surface of the material.

With a $\frac{1}{8}$ -inch thick metal cover in place, the box is first "tuned" by adjusting its length until the output of the microphone, as read on a sound level meter, is maximum. Sound level meter readings are then obtained for several calibrated 1 foot by 3 foot samples that are placed in turn on the box under the metal plate cover. Readings on the unknown samples are interspersed with those on the calibrated samples. The coefficients of the calibrated samples, which have been previously measured in a reverberation chamber, are then plotted as a function of their sound level meter readings. The absorption coefficient for the unknown sample is then spotted on the curve from its sound level reading.

Rapid Method Determines Curvature and Second Derivative of a Plotted Curve

A convenient graphical method developed by Dr. H. L. Curtis of the National Bureau of Standards makes possible the quick and accurate determination of the curvature and second derivative at any point on a plotted curve. The method¹⁵ utilizes an easily constructed device known as an "Osculometer," a piece of



The box method is not suitable at very low or very high frequencies; the box at the National Bureau of Standards is used only at 512 cycles per second. At this frequency the correlation between box and reverberation chamber measurements is best. Even so the errors are rather large, amounting as they do to a probable error of ± 0.05 in the coefficient. Moreover, the method requires a set of reference samples covering a rather wide range of sound absorption coefficients. Also, the presence of an airspace behind the sample often leads to erratic results, so that the box method as described is used only for measurements with the sample mounted against a rigid backing.

Like the tube method, the box method suffers because actual installation mounting conditions cannot be duplicated very closely. Its principal advantage is for control checking, since the commercial tile size samples required are not mutilated in any way during a test, and the measurements are rapidly made.

transparent material containing a series of arcs of known curvature. Curvature is read by direct comparison of the experimental curve with the osculometer, and the corresponding second derivative is then obtained by a simple calculation. Although the osculometer was originally designed at the Bureau to aid in the analysis of extensive data resulting from a research program on interior ballistics, the method should provide a useful tool in a number of other fields—such as aerodynamics, mechanical engineering, and electrical design—where graphical methods of computation are widely used.

In the Bureau's work on interior ballistics, the acceleration of a projectile was at first determined by plotting two curves on a large scale. Tangents to the first curve, a plot of displacement against time, were obtained at a number of points and were plotted against time to give the second curve, which represented the velocity-time relationship. The tangents to the second curve then gave the instantaneous acceleration as the second derivative of displacement with respect to time. Use of the osculometer was found to simplify the process greatly, eliminating the necessity of plotting the intermediate velocity curve.

In making measurements with the osculometer, a point on the curve is selected at which a value of the second derivative is desired, and an osculometer is chosen having arcs within the proper curvature range.

¹⁵ For further technical details, see Determination of curvature by an osculometer, by Harvey L. Curtis, J. Research NBS **44**, 131 (1950) RP2063.

The osculometer is essentially a piece of transparent material on which are drawn a series of arcs of known curvature. When these arcs are fitted to an experimental curve, its curvature is read directly from the scale of the instrument. Slope is also given by a simple measurement.

When an arc has been fitted to the curve at the selected point, the curvature, C , is read directly from the osculometer, and the corresponding slope is determined with a protractor by measuring the angle θ between the base of the osculometer and the positive direction of the X -axis. The second derivative of the curve is then computed from the equation

$$\frac{d^2 y}{dx^2} = C \sec^3 \theta.$$

This equation is easily derived from the familiar expression for radius of curvature.

Several types of osculometers have been developed. The simplest form consists of a transparent sheet of plastic on which black circular lines having uniformly increasing curvature are spaced at regular intervals. A scale at one side gives the curvature of the arcs in reciprocal centimeters. This type of osculometer has

the disadvantage that the curve under study is obscured while an arc is being fitted to it, and various methods of avoiding the difficulty have been worked out. For example, the arcs may be made as clear lines in an opaque or semiopaque sheet. The curve to be studied is then drawn on translucent paper, and comparison is made on a diffusing surface illuminated from beneath. Another method is to make each curve a series of dashes. Perhaps the best solution is the double-line osculometer. For each degree of curvature, two identical arcs are drawn about 1 millimeter apart. Then the curve under observation can be made to lie between the two arcs having a curvature equal to its own. With such an instrument, curvature can usually be determined to 0.001 reciprocal centimeter, provided the curvature is approximately constant for a distance of 2 centimeters on either side of the point at which it is measured.

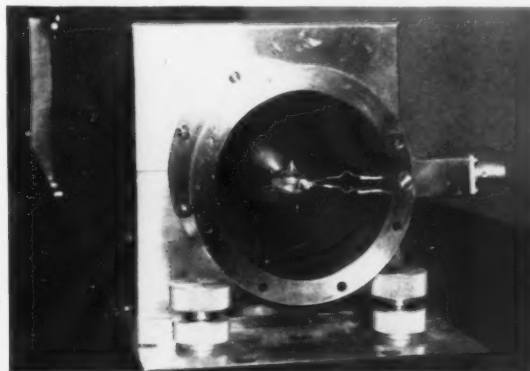
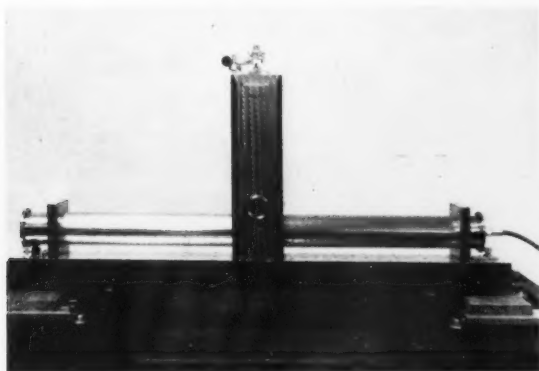
Electrodynamic Ammeter for Very High Frequencies

In establishing standards for electrical circuits in the very-high-frequency region now so widely used by radio and television services, it is important to extend the direct measurement techniques used at lower frequencies as far as possible. Up to 300 megacycles per second the current flowing in a circuit whose physical dimensions are small with respect to wavelength is essentially a uniform quantity, and the electrical characteristics of small circuit elements may be determined directly in terms of voltage and current. This fact makes possible the establishment of a standard electrodynamic ammeter for the VHF range.

Such an electrodynamic ammeter design, employing a short-circuited ring coupled to a coaxial transmission line, has been the subject of a theoretical and experimental study by Max Solow of the National Bureau of Standards. His work extends a previous study by Turner and Michel at Yale University.

Basically the method depends on a torque measurement on a conducting ring immersed in a field that does not change with frequency. This technique provides an absolute, broad-band measurement of high-frequency current, but several factors are critical in any actual design.

For minimum distributed capacitance and uniform current the short-circuited ring must be only a single turn, and the ring diameter must be small with respect to wavelength. For accurate inductance calculations the ring conductor should have a small cross section, but resistance then limits the current. A ring 1 centimeter in diameter of No. 20 copper wire is a practical size. When the ring current is small, the torque is also small, and the ring must be suspended on a delicate quartz fiber for accurate torque measurements. The coaxial line, acting as the primary current-carrying element for the electrodynamic ammeter, has several



The electrodynamic ammeter for very high frequencies (experimental model, left) consists of a coaxial transmission line (horizontal tube) and a short-circuited ring between the inner and outer conductors of the line. The ring is suspended from the central tower by a quartz fiber. When current is flowing in the line, a torque is produced on the ring; the amount is indicated by light reflected from a mirror on the quartz-fiber suspension. (Right) A thermocouple element is in place for calibration (end view). When in use, copper plates cover the ends to isolate the ammeter from external fields.

advantages over other forms of conductor. Its electromagnetic field can be calculated in a straightforward manner, and the line may be readily modified for calibration work with different types of radio-frequency ammeters.

Calibration of the electrodynamic ammeter may be accomplished directly and absolutely. A section of the coaxial transmission line, one wavelength long at 300 megacycles, is arranged with short-circuited ends to form a resonant cavity, and the torque ring is placed midway along the section. A known value of 300-megacycle power is fed into an input loop at one end of the cavity. Under these conditions the torque ring will be at a current maximum and a voltage minimum, and the measured torque on the ring will be due almost

entirely to the magnetic component of the cavity field. The measurement is then repeated at 150 megacycles where the current and voltage relations are reversed, and the torque is due only to the electric component. One further measurement is needed for absolute calibration of the ammeter. The cavity resonance frequency is measured at both 300 and 150 megacycles with and without the torque ring in place. The resulting changes in frequency are then a measure of the field discontinuity introduced by the presence of the ring. After the torque and discontinuity measurements are completed, the instrument will be ready for use as a standard to calibrate other ammeters at very high frequencies.

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- Journal of Research of the National Bureau of Standards, volume **44**, number 6, June 1950. (RP2103 to RP2107, incl.)
Technical News Bulletin, volume **34**, number 6, June 1950. 10 cents.
CRPL-D69, Basic Radio Propagation Predictions for September 1950. Three months in advance. Issued June 1950. 10 cents.

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